

Eye-Safe Laser Radar 3-D Imaging

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Abstract

This paper reviews the progress of Advanced Scientific Concepts, Inc (ASC). flash ladar 3-D imaging systems and presents their newest single-pulse 128 x 128 flash ladar 3-D images. The heart of the system, a multifunction ROIC based upon both analog and digital processing, is described. Of particular interest is the obscuration penetration function, which is illustrated with a series of images. An image tube-based low-laser-signal 3-D FPA is also presented. A small-size handheld working version of the 3-D camera is illustrated which uses an InGaAs lensed PIN detector array indium bump bonded to the ROIC.

Keywords: Flash Ladar, 3-D Imaging, 3-D Focal Plane Array

1. Introduction

Although 2-D and 2-D range gated images are potentially very useful for locating and identifying objects, the information that can be extracted from a silhouette image is limited. Adding an additional dimension, range, is desirable as a method of improving our ability to extract objects from background interference and to provide additional feature information that improves that capability of automatic target recognition algorithms. An ideal 3-D imaging system would be one that could capture all of the scene information at a single shot or laser flash. This 3-D flash ladar image approach would freeze each pixel in relation to the others reducing the need for preprocessing of the image to correct pixel registration. Pointing speed, accuracy and agility requirements would be reduced to what would be needed in order to track the target. Because the entire scene would be illuminated, the per pulse energy requirements would be similar to those for a range gated approach. But, because only one pulse would be needed for each frame, the average laser power required would be less, comparable with that needed for a single pixel scanned ladar approach. Furthermore a 3-D flash ladar approach has the potential of generating time resolved 3-D movies for increased target information.

This paper is organized as follows: First the components of a 3-D imaging flash ladar system are described. The most critical component, the 3-D FPA is then discussed. Functionality of the 3-D FPA is determined by the Readout Integrated Circuit (ROIC) and the ASC-designed, AVDAR ROIC is discussed in Section 3 along with images captured with a 128 x 128 AVDAR ROIC. Detectors incorporating gain are important for compact systems and ASC's Image Tube approach is described in Section 4.

The ASC hand held 3-D imaging flash ladar system is depicted in Figure 1. It is representative of a flash ladar system. The system consists of a laser transmitter which together with the transmit optics directs a laser pulse at a target. The receive optics collects the target-reflected light and focuses the laser light on the 3-D FPA. Drive electronics provide the clocks and biases that operate the sensor and the output electronics conditions and digitizes the data output from the sensor, and then transfers the data to the processing computer for further 3-D processing and display. In Figure 1 the drive and output electronics circuit boards are inside the camera housing. The laser transmitter is also inside the camera housing.

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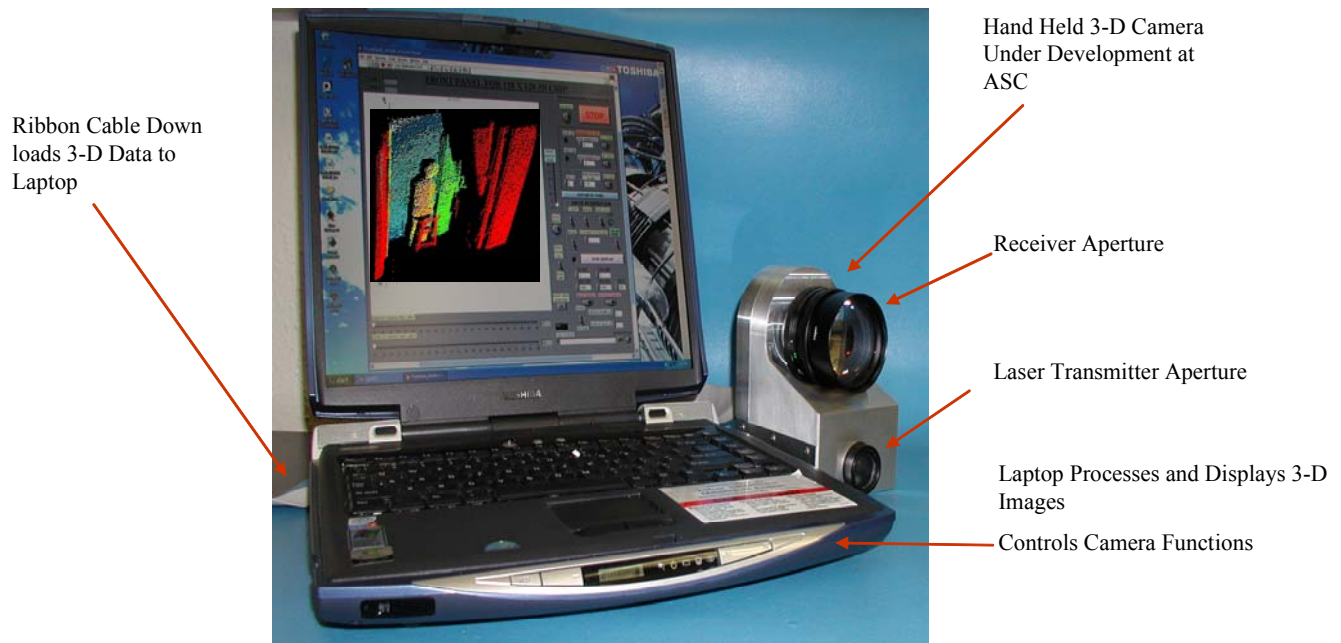


Figure 1. Representative 3-D Flash Ladar Imaging System

2. The Hybrid 3-D FPA

Typically the 3-D FPA is a Readout Integrated Circuit (ROIC) bump bonded to a solid state detector array to form a hybrid. Each unit cell, operated independently of the other unit cells in the array, is bump bonded to an independent detector in the detector array. The general hybrid design is depicted in Figure 2.

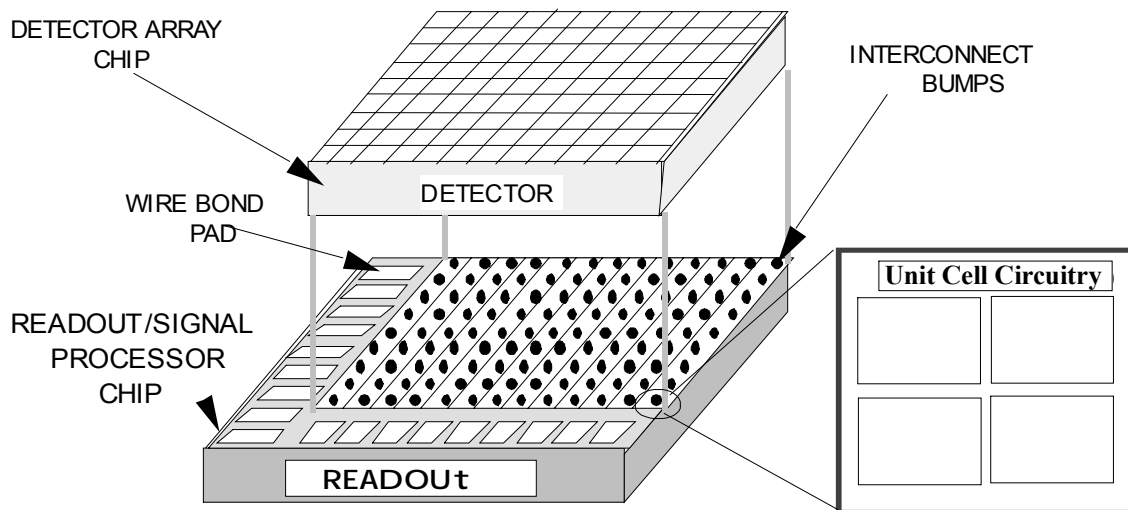


Figure 2. 3-D FPA Hybrid Design. ROIC bump bonded to detector array chip

The Figure 2 hybrid 3-D FPA design is a very general configuration and can be used with a variety of detectors. For example silicon InGaAs or HgCdTe PIN or APD arrays. 3-D FPA gain is important for reducing laser power and developing compact systems. InGaAs or HgCdTe arrays allow for eye safe operation. For all the images discussed in the next section the eye safe laser wavelength was 1.54 μm and the detector array was InGaAs. An alternate image tube, high-gain, 3-D FPA design is described in Section 4.

The Readout or ROIC in Figure 2 is the critical component in the hybrid. Fundamentally each pixel contains circuitry, which independently counts time from the emission of a laser pulse, from the camera, to the capture of the reflected pulse in a pixel.

In addition pixel circuitry captures temporal information about the returned pulse. Pixel and ROIC circuitry support additional functions. For the ASC-designed AVDAR ROIC all functions are described in the next section.

3. The Multi-Function 128 x 128 AVDAR 3-D ROIC and Single Laser Pulse (Flash) 3-D Images

The 128 x 128 AVDAR ROIC performs its functions by a unique combination of both analog and digital circuitry. Figure 4 illustrates these functions.

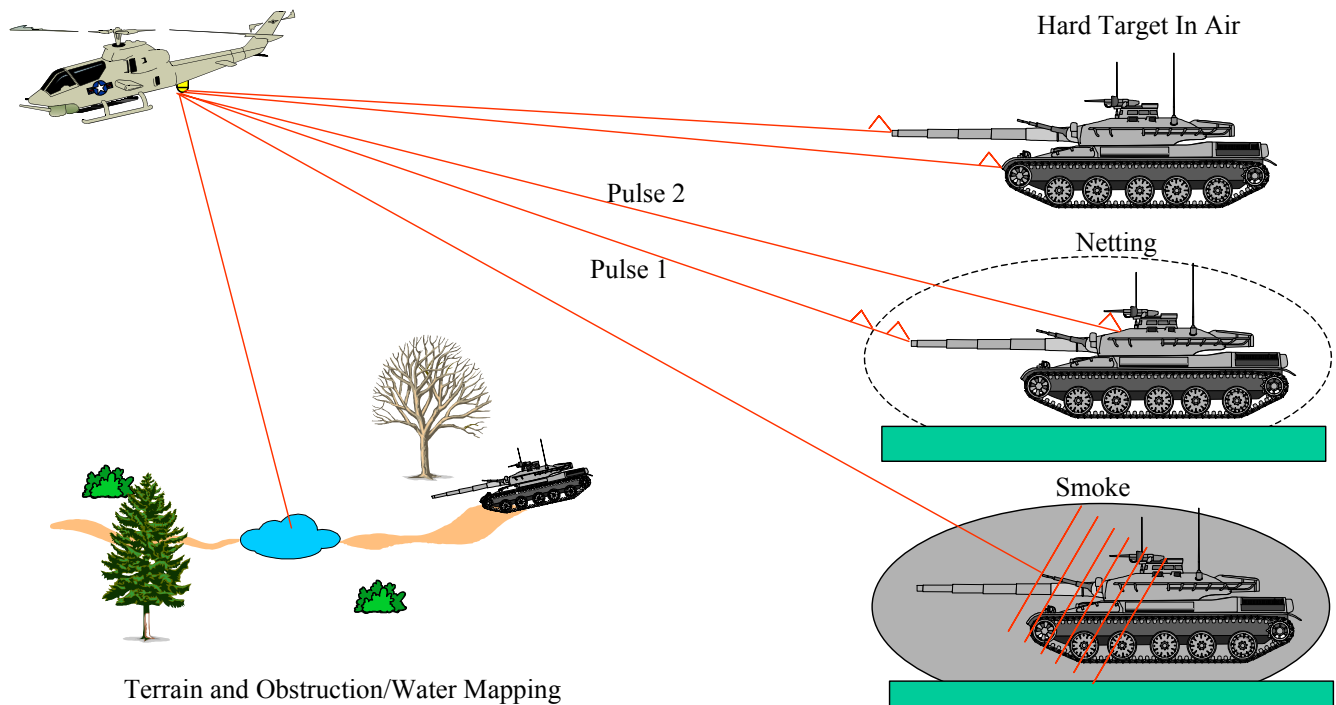


Figure 4. Function of AVDAR ROIC: hard target 3-D imaging, 3-D imaging through camouflage, 3-D imaging through smoke and 3-D imaging through water.

A short laser pulse is emitted from the laser transmitter on the helicopter in Figure 4. The transmitter optics spreads the beam out over the field-of-view of the receiver, which covers the entire target object. In the top diagram of Figure 4, Hard Target in Air, those points on the target, which are closest to the receiver/transmitter, such as the tank cannon, reflect light back first. As the laser pulse propagates across the target, laser light is progressively reflected back to the receiver from all points of the target facing the receiver. Each pixel at the 3-D FPA, see Figure 2 for example, is able to capture the individual round trip time to the target and in addition other circuitry captures the returning pulse shape. This additional information is used to increase the range precision, increase the range resolution, detect multiple targets in a single pixel and provide still further information about the target. By capturing the range to the target for each pixel in the two dimensional focal plane, the third dimension is produced. By use of proper algorithms, and both the analog and digital data, sub-inch range precision can be achieved for relatively modest signal-to-noise ratios (typically on the order of 10 - 20) with reasonably long pulse lengths (typically a full width half maximum equal to 5 ns). Minimal analog-data processing, can be used for standard 3-D images, with range precisions of about 6 inches. Figure 5 illustrates a hard target image.

In the second diagram from the top in Figure 4, Hard Target Response Thorough Camouflage Netting, the first return for most of the pixels is the netting. Assuming some net transparency, the pulse capture circuitry allows a second return to be distinguished if the target is beyond the net. For objects deeper than 20 feet, the receiver can be programmed, for the second laser pulse, to ignore the net return and react only to targets beyond the net or to targets beyond a programmed range.

In the third diagram from the top in Figure 5, Penetration Thorough Smoke, the hard target first return circuitry is suppressed and pulse capture circuitry is turned on after a specific range. Reflection from a hard target in the smoke will

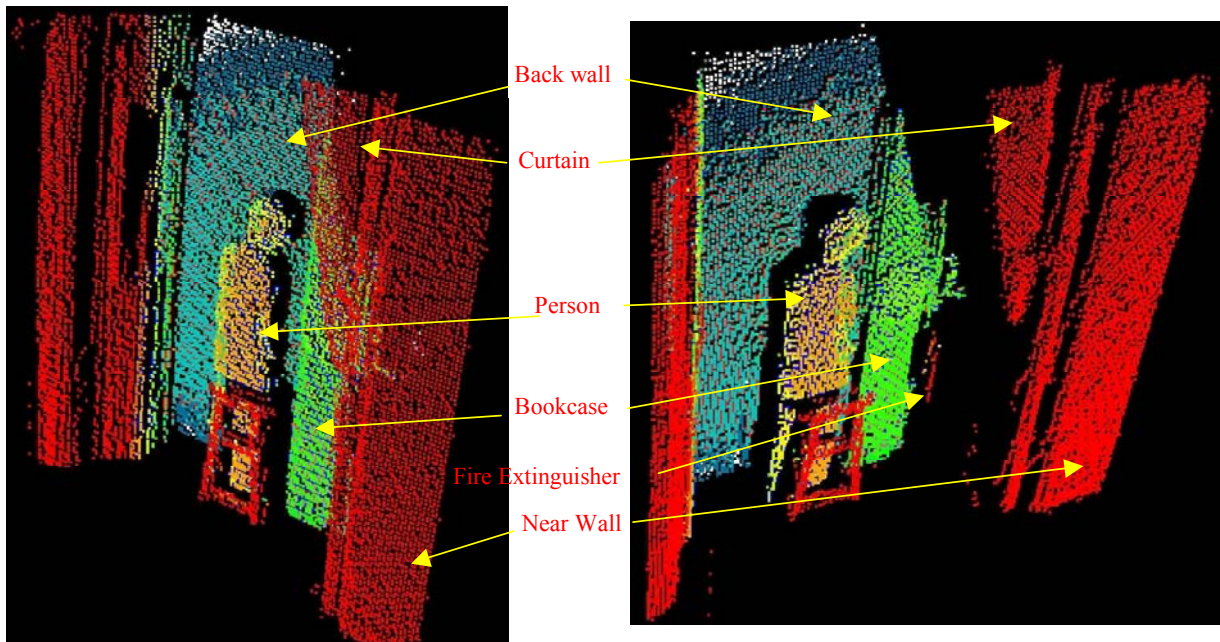


Figure 5 a and b. Two different angles of the same hard target 3-D 128 x 128 single-pulse flash ladar image; raw unprocessed and uncompensated data with the simplest range algorithm. Color-coded range.

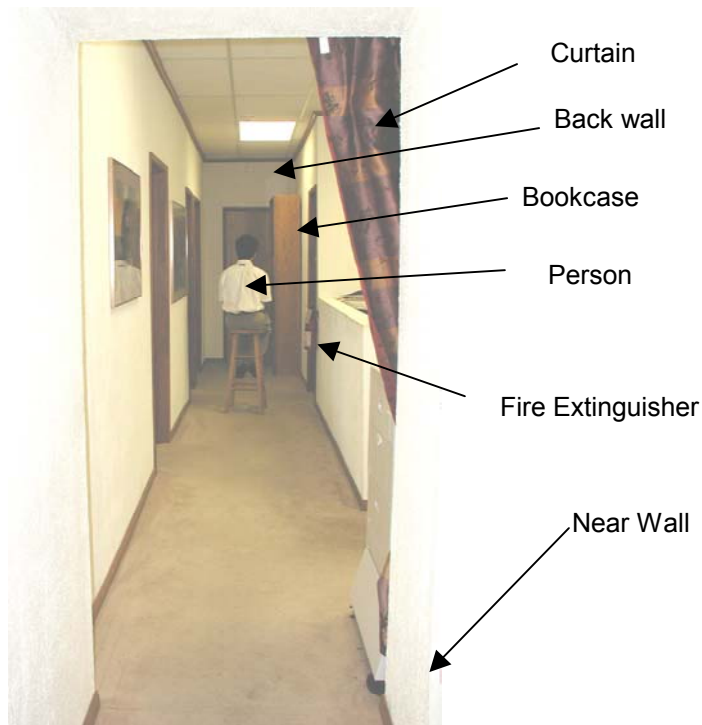


Figure 6. 2-D Image associated with Figure 5.

dominate the reflection from the smoke in the sample. Just as for hard targets in the atmosphere, parts of the target which are deeper in the smoke will show up on later samples in the two dimensional focal plane, giving the third dimension. The twenty

samples available in the AVDAR design can be made to scan through the smoke with progressive laser pulses and processing algorithms can produce a 3-D image of the target in the smoke.

Figure 8 illustrates the raw data from obscuration penetration without the smoke. This is similar to the penetration through netting with the targets located far from the netting.

In the fourth diagram from the top in Figure 6, Penetration Thorough Water Obstructions, the hard target response threshold circuitry is also suppressed and the pulse capture circuitry finds the bottom much like a target is found in smoke. The difference is that a different laser should be used. Usually longer laser wavelengths penetrate smoke best while the best water penetration is with .53 μm .

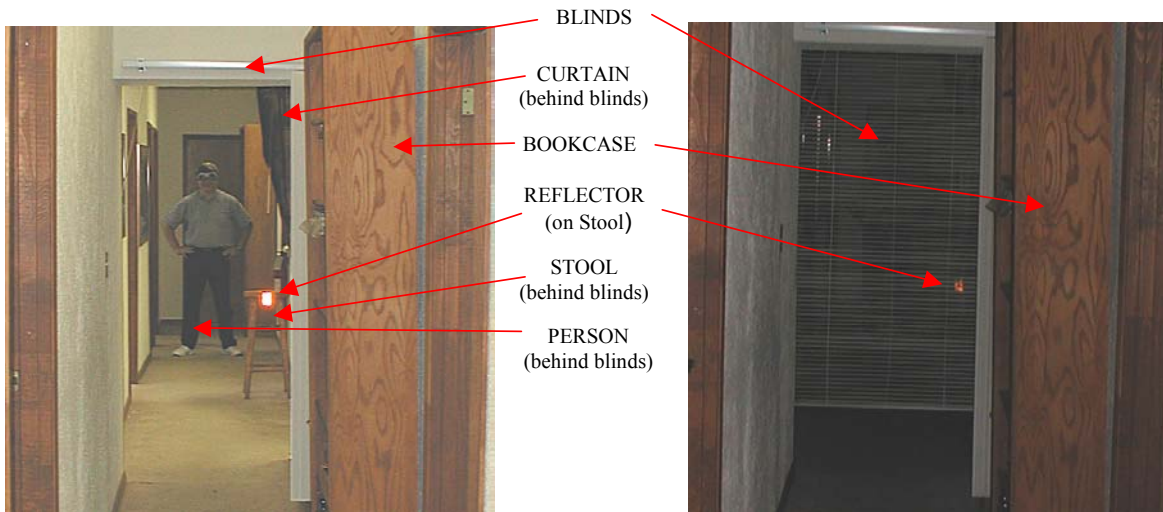
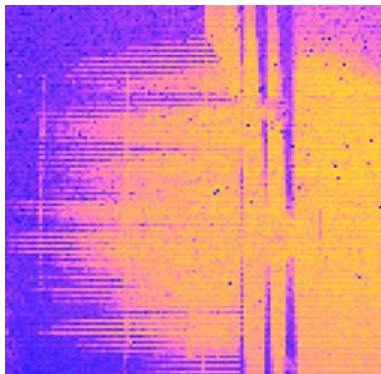
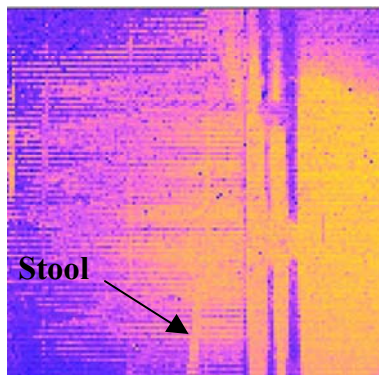


Figure 7. 2-D Pictures of Camouflage Penetration Experiment. (LHS) Blinds pulled up to show person and stool behind blinds. (RHS) Blinds down and closed 50%. Stool and person are totally obscured in the 2-D image. Some light from the reflector on the stool appears in the 2-D image.

Time slice # 1: Laser Pulse Penetrates Blinds; Bookcase and Curtain are shadowed



Time slice # 6: Laser Pulse reflects from Stool; Bookcase and Curtain are shadowed



Time slice # 10: Laser Pulse reflects from Person; Stool, Bookcase and Curtain are shadowed

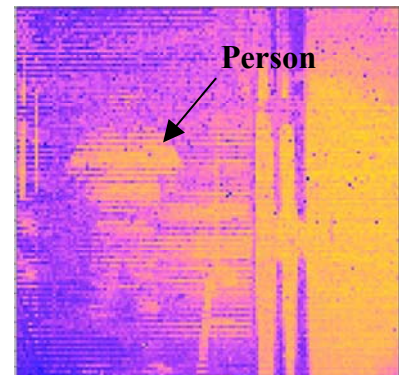


Figure 8. Obscuration Penetration with the Current 128 x 128 ASC ROIC: Single laser pulse, raw unprocessed and uncompensated data. Selected time slices from behind obscuration. Each pixel captures multiple consecutive time slices.

The 3-D FPA used in producing the Figure 5 and Figure 8 images was the Figure 2. hybrid where the detector array was InGaAs PIN diodes. In order to reduce capacitance the junction area was small and lenses etched into the substrate were used to increase the fill factor. Reference 1, a companion paper, discusses 3-D flash imaging with a lensed APD array using a

32 x 32 AVDAR ROIC. In the next Section we discuss progress in 3-D Image Tube FPAs, a very promising low noise, high gain technology.

4. Image Tube 3-D FPA Progress

Detector gain technology is important for reduction of laser power and the image tube 3-D FPA is important example of this technology. The image tube gain technology is made possible by the development of eye-safe photocathodes (References 2 and 3). Figure 3 illustrates an electron bombarded (EB) image tube 3-D FPA.

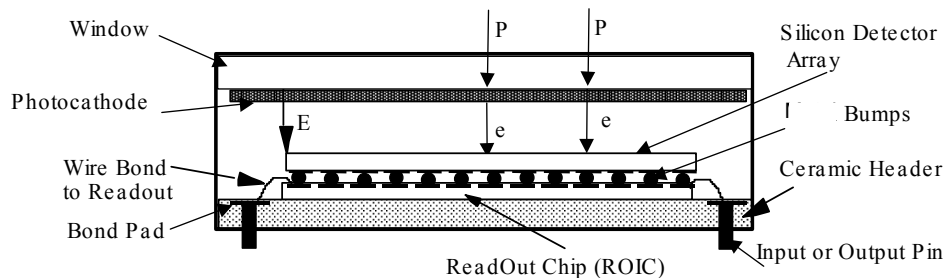


Figure 3. Electron Bombarded (EB) Image Tube 3-D FPA

The image tube 3-D FPA works as follows: photons pass through the window and interact with the photocathode producing a photoelectron. This electron is accelerated by the electric field E through a potential measured in kV and penetrates into the silicon of the hybrid causing gain by impact ionization. Approximately one electron-hole pair is produced for each 3.6 eV for those photoelectrons which penetrate into the active silicon region. The noise factor is less than 1.1.

If all the parameters of the imaging system were held constant, except for the detector array, it is anticipated that the image tube with current photocathode quantum efficiency would be effective at a range that was 3 times greater than a lensed InGaAs PIN array.

4. Conclusions

This paper presented 3-D Flash ladar imaging results from ASC's newest imaging system. These results illustrate the versatility, usefulness and promise of the AVDAR ROIC approach to 3-D ladar.

5. Acknowledgements

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3. Verle Aebi, et al, Gallium Arsenide Electron Bomb. CCD Technology, SPIE Conf. on Image Intensifiers and Appl., July 1998.

3-D Volume Data



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Approaches/Problems

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- **Single element raster scan**
 - **High speed, stable optics**
 - Repeatability
 - Speed across image
 - **High laser pulse rates**
 - 1 Pulse per pixel
 - **Intense pixel registration**
 - Image skewing due to motion, time lapse
 - Preprocessing required to 'straighten' image

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2

Several approaches have been tried to produce 3-D images. Three of the most direct laser radar (Ladar) approaches are the following:

A single narrow laser beam is rapidly scanned across the image field of view. The laser must be pulsed and the return from each area of the image is timed. The corresponding range to each of these pixels is mapped out to produce the 3-D image of the scene.

Because this approach uses some type of raster scan to cover the entire scene, high speed and stable optics are needed to steer the beam. Any pointing errors can cause gaps or overlap in the image or cause the image to jump from frame to frame.

Also, the required laser pulse repetition rate is very high because reading each pixel requires at least one laser pulse.

It takes a finite period of time to scan a complete frame and any relative motion between the target and the sensor platform will cause the image to be distorted. This distortion creates an extra processing overhead that affects system requirements.



Imaging Approaches (cont)

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- **Flood illuminated range gating**
 - **Single range bin per pulse**
 - Multiple range slices
 - **High timing accuracy requirements**
 - Creates gaps or overlaps
 - **Lower laser rate, higher energy**
 - One pulse per range slice
 - Entire scene illuminated with each pulse
 - **Layer registration**
 - Multiple overlays for each pixel

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3

The second type of 3-D imaging uses a range gating approach. The laser beam width is increased so the entire Field of Regard (FOR) is illuminated with a single pulse. The receiver consists of an array of detectors that can be switched on and off very quickly and precisely. To build up the image, the detector is turned on and off once for successive laser pulses at different times. Each capture image represents a range slice in the image. Each of these slices is stacked up to produce the final 3-D image.

Because the sensor is operating in a staring mode, the requirements on the optical system are significantly reduced, primarily requiring enough stability to prevent jitter between each of the slices. However, such a system demands a very high timing accuracy in order to prevent gaps or overlaps between the slices.

While the required laser pulse rate for this approach is lower than in the raster scan, the framing rate times the number of range slices to be captured, the need to flood illuminate the entire FOR can mean that this approach has the highest average power laser requirement.

As in the previous approach, any relative motion between the target and sensor or optical and timing jitter will require significant preprocessing of the image.



Imaging Approaches (cont)

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- **Flood illuminated single shot imaging**
 - **Array sensor - one detector per pixel**
 - Pixels remain fixed in position
 - **Lower scanner requirements**
 - No scanning within field of view
 - Target tracking slower than scanning
 - **High pulse energy (same as range gating)**
 - **Lower pulse rate - one per image**
 - Low average laser power

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4

A sensor design that could make all of the required pixel measurements simultaneously would greatly relax the requirements for both optical system stability and computer algorithm capability.

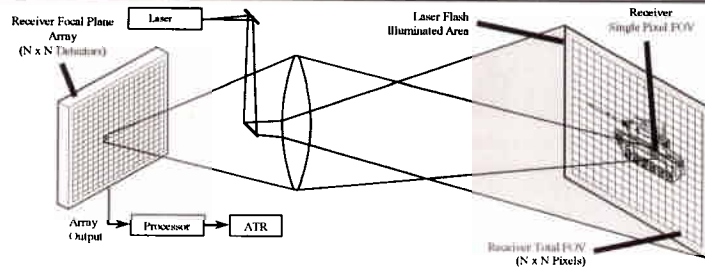
Using an array of detectors and a single short laser pulse would mean that all of the pixels remained properly aligned. Because the system would be operating in a staring mode, no high speed scanning would be needed, only enough agility to keep the target area in the field of view.

Illuminating the entire scene would require the same per pulse energy as for the range gated approach. However, because all of the range bins are collected from the same pulse, the laser pulse rate is reduced to only one per frame, the laser power requirement is greatly reduced.



Basic 3-D Imaging Concept

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- **X-Y resolution based on pixel size and optics focal length**
- **Z resolution based on estimation of pulse time-of-flight**
- **Intensity of return pulse based on range and reflectivity**
- **Reduces scanner requirements**
- **3rd dimension increases algorithm robustness**
- **No complicated laser waveforms**
- **Reduced processing requirements**

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5

The Flash 3-d Imaging concept described in the previous chart is illustrated in this diagram. This approach is made possible by the development of the specialized Read-out Integrated Circuit (ROIC). The ROIC contains all of the circuitry time and sample the return pulse. Using this ROIC can greatly reduce scanner and processing requirements. This ROIC is bonded to a similarly sized detector array to make up the receiver hybrid.



Flash 3-D Ladar Image Capture Sequence

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- **Single Laser Pulse Illuminates a Large Surface Area Like A Digital 2-D Flash Camera.**
- **Pulse Returns from the Surface are Focused On an Array of Smart Pixels**
- **Smart Pixels Collect and Store Digital and Analog Data Representative of the Flight Time and Laser Pulse Characteristics**
- **All Data is Output Between Laser Pulses**
- **Data is Processed In FPGA In Real Time To Yield Point Cloud Coordinates**
- **Camera Measures Time of Flight Of Laser Pulse for 16,000 Points Simultaneously (128x128 Array), 20 Analog Samples (420 MHz – corresponds to 0.36 meters)**

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6

The sequence of events in capturing a 3-D laser radar image are as follows:

A single laser pulse is transmitted with a beam shape that matches the field of view of the receiver.

This outgoing pulse starts the clock that is used to determine time-of-flight (TOF) and to calculate range.

The returning signal is collected and focused by the receiver optics onto the detectors of the receiver.

ROIC circuitry determine the TOF and sample the return pulse independently for each pixel.

The data is output to the control processor where it can be processed, stored and displayed.

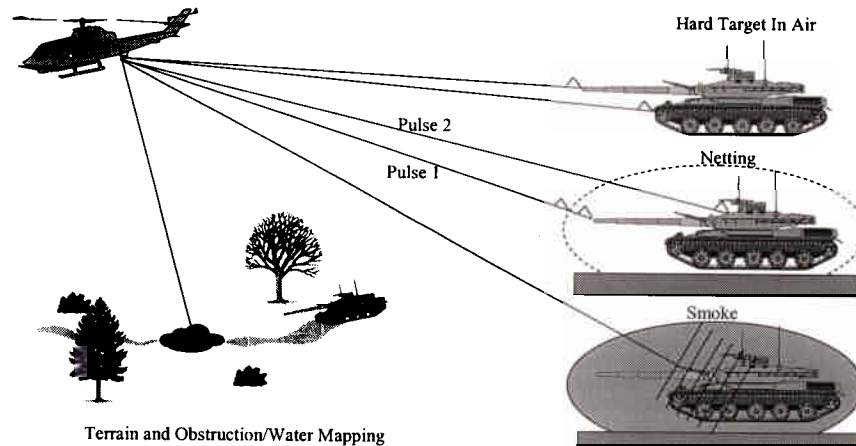
The current design is a 128x128 pixel array that can capture 20 samples of the return pulse at a rate that is equivalent to step sizes of 0.36 meters



Multi-mode Operation

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Chip has peripheral circuitry for supporting multiple returns (i.e., smoke penetration)



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7

The receiver can be operated in 3 different modes.

In Mode 1, each pixel operates independently through an internal threshold sensing circuit. When the input signal in the pixel exceeds the threshold, the timer is stopped and the sampler is also stopped shortly afterwards. The data in the file then represents the time (or range) from which the signal was reflected. This mode is most useful when the targets or 'region of Interest' is in the open.

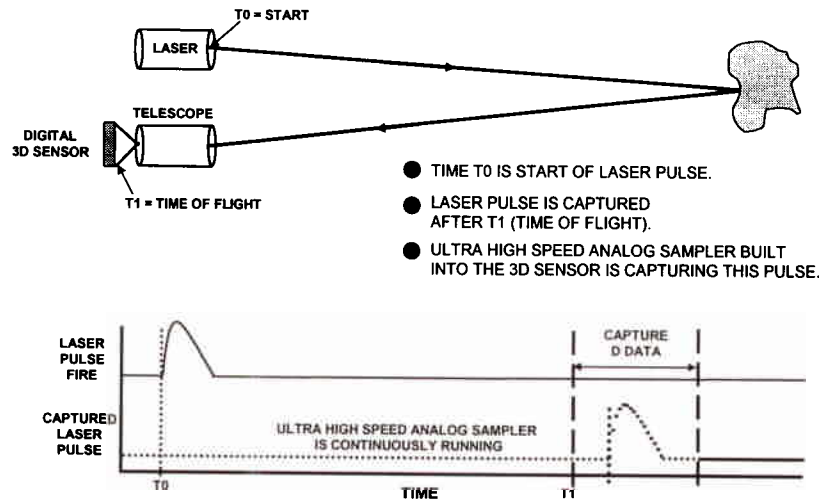
Mode 2 is similar to Mode 1, except that the clock and threshold detector can be delayed by some fixed amount. This allows the sensor to ignore returns from intervening interferants such as camouflage and trees.

In the final mode, the threshold signal is turned off and the samplers are started by an external signal. The samplers for all of the pixels are synchronized and the result is a data cube that represents the 3-D reflectivity of the volume sampled.



Return Signal Captured in 20 Samples (1 nanosecond represents 0.15 m)

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8

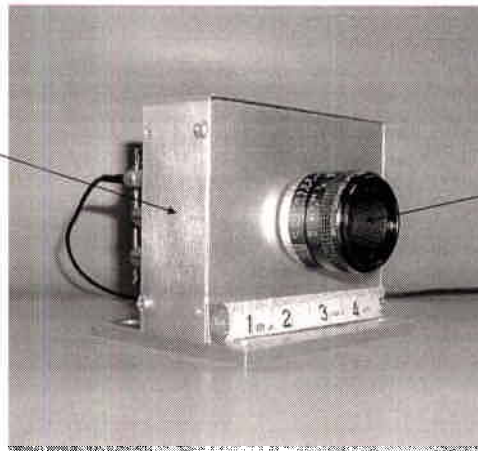
This slide illustrates Mode 3 operation. The sampler is turned on a time T1 and 20 analog samples of the return pulse are captured. This operation is carried out simultaneously in all of the pixels in the receiver.



Current 128 X128 Test Configuration

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3-D Camera



3-D Camera
Lens

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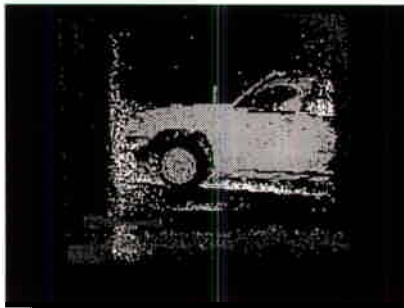
9

This is a view of the current test camera. In this version, the detectors used are InGaAs diodes sensitive to 1.5 microns.



Single Shot Ladar Images

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10

These simple images were captured with the current device and help to illustrate the level of information available from these types of data. In these examples, range is depicted by color. Because range information is an integral part of the data, scaling is automatically accomplished. The 3-D nature of the data allows the images to be rotated about an axis in order to provide alternative views of the image.



IMAGE OF RAW DATA (OUTPUT FROM THE 3D SENSOR)

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Stepping through 20 samples captured with a single laser pulse



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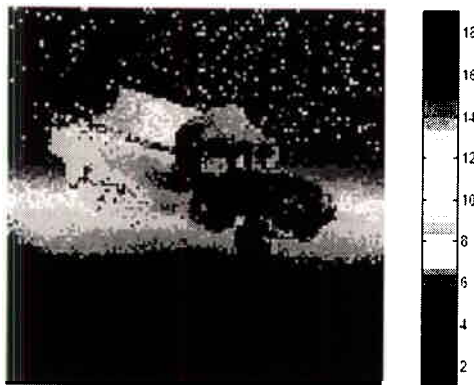
11

In this image, the target was a military style 2 ½ton truck. The 20 samples of the return pulse amplitude are displayed sequentially as individual frames in the movie. Each frame represents approximately 0.35 meters farther down-range. Since the truck was viewed from an angle off the right side of the vehicle and from an elevated position, the progress of the pulse as it traverses the target can be observed.



3-D Image

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12

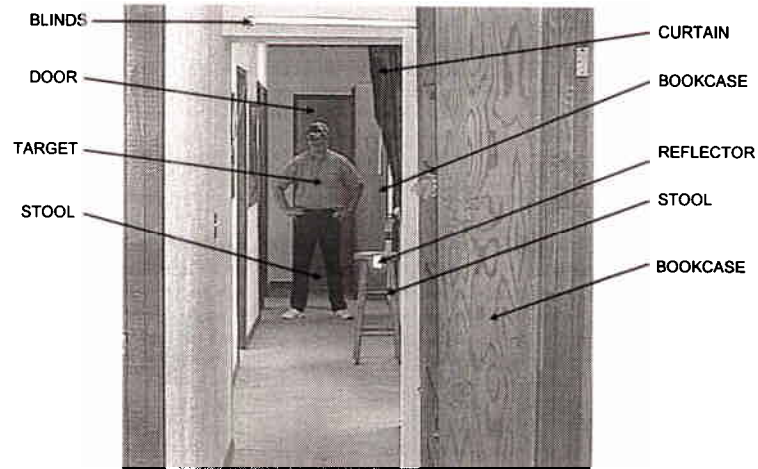
Here the data from the previous slide was used to create a '3-D' image where range is displayed by color.



SETUP FOR 128 X128 FLASH LADAR SENSOR CAMOUFLAGE SEE THROUGH TEST

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Scene before blinds are lowered



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13

A simple camouflage demonstration was set up. In this view, the target scene is displayed.

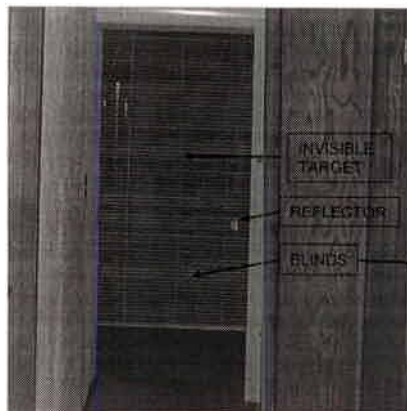


128 X128 FLASH LADAR SEES THROUGH CAMOUFLAGE (45% OBSCURITY)

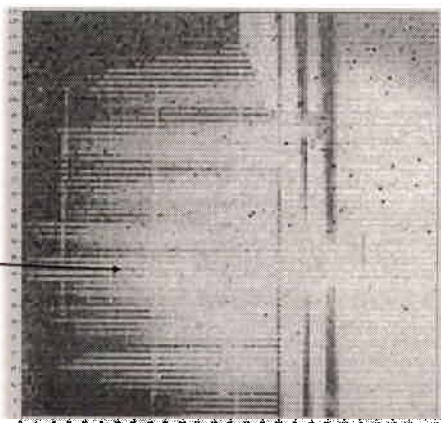
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Stepping through 20 samples captured with a single laser pulse

OLYMPUS DIGITAL CAMERA IMAGE
With blinds lowered



128 X 128 FLASH LADAR IMAGE



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14

The frame on the left is the same scene as in the previous slide, but a Venetian blind has been lowered to obscure the target area. The movie on the right again displays the range slices captured by the sensor. As the pulse propagates through the target area, first the blind is displayed. Later, the stool behind the blind begins to be visible. Farther into the scene, the man begins to be detectable. And finally, his silhouette on the wall is visible.



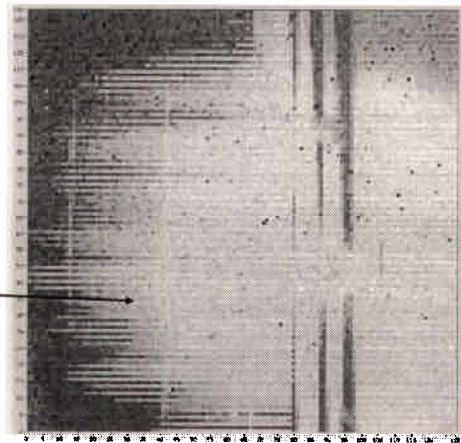
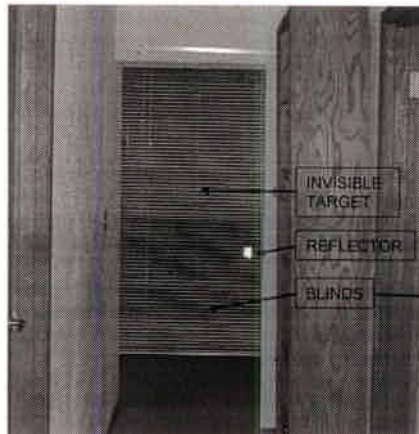
128 X 128 FLASH LADAR SEES THROUGH CAMOUFLAGE (60% OBSCURITY)

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Stepping through 20 samples captured with a single laser pulse

OLYMPUS DIGITAL CAMERA IMAGE
With blinds lowered

128 X 128 FLASH LADAR IMAGE



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15

This scequence illustrates the same scene with the blinds now set to provide 60% obscurity.



Conclusions

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- **3-D laser radar offers a unique sensor capability**
- **Return signal sampling makes it possible to 'see through the holes'**
- **Range information not only provides target shape, but automatically allows for scaling of images for use with ATR algorithms.**

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16